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Radiative properties of a turbid medium underlying-surface system

A. A. Kokhanovsky
University of Bremen
Institute of Environmental Physics
Otto Hahn Allee 1
D-28334 Bremen, Germany
and
National Academy of Sciences of Belarus
Institute of Physics
70 Skarina Avenue
Minsk 220072, Belarus
E-mail: alexk@iup.physik.uni-bremen.de

Abstract. Calculations of the spectral cloud reflectance over bare soil and vegetation are performed in the framework of the asymptotic radiative transfer theory. A simple equation for the threshold value (THV) of the albedo of the underlying surface is derived. The cases of underlying surfaces with the albedos smaller than the THV can be treated as if the albedo of the surface is equal to zero in satellite cloud remote sensing problems.. It was found that the THV increases with the cloud optical thickness. Also, the differences in light transmission by clouds over bare soil and vegetation are studied. [DOI: 10.1117/1.2402105]

Subject terms: radiative transfer; cloud remote sensing.

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1 Introduction

Spectral reflection and transmission characteristics of turbid media are of importance for a number of applications (e.g., oceanic and atmospheric optics). Reflection and transmittance of light by random media can be studied in the framework of radiative transfer theory, which is based on the integro-differential radiative transfer equation.[1,2] Theoretical results can be obtained both for an underlying black surface (e.g., clouds over ocean in the IR) and for bright surfaces (e.g., sand and snow in the visible).

One can derive the following simple relationship between the cloud reflectance R_b for the case of black ground and the cloud reflectance R for the case of a Lambertian ground with albedo A:[2,3]

$$R = R_b + \frac{At_1t_2}{1-Ar}, \tag{1}$$

where $R_b \equiv R(A=0)$, r is the spherical albedo of a cloud over the black surface, and t_j is the cloud's total transmittance in the direction specified by the solar ($j=1$) or observation ($j=2$) zenith angle (at $A=0$). Zenith angles are measured from the normal to a scattering layer.

The measured value of R is often used for the estimation of the optical thickness of the medium. In particular, satellite remote sensing of clouds is performed by fitting measured spectral cloud reflectances $R(\lambda)$ (where λ is the wavelength) to synthetic ones.[2] The problem is that in the case of thin clouds the underlying surface may considerably change the registered spectra. Therefore, there is a need to take account of the underlying surface reflectance A in cloud retrieval algorithms. The value of A is not known *a priori*, which constitutes a major problem for satellite thin-cloud retrieval algorithms. However, in some cases (thick clouds over dark surfaces, e.g., water) there is no necessity to take account of the surface contribution, because it is very weak. The corresponding measurements of $A(\lambda)$ can be found, e.g., in the work of Krinov.[4]

The main task of this paper is to calculate the boundary value of the underlying surface reflectance A^* having the property that the reflection function R of the cloud–underlying-surface system differs by not more than a given amount ς from the value of R at $A=0$ for all $A \leqslant A^*$. This information is of importance for understanding if the surface contribution must be taken into account in the retrieval algorithm for a given cloud field. The value of ς can be taken equal to the calibration error of the optical instrument used for the measurements.

We also considered the influence of underlying surface on the cloud transmittance.

2 Reflectance

The boundary value of A^* can be easily found from Eq. (1). Namely, it follows that

$$\frac{A^*t_1t_2}{(1-A^*r)R_b} = \varepsilon, \tag{2}$$

where $\varepsilon = (R-R_b)/R_b$. We obtain from Eq. (2)

$$A^* = \frac{\varepsilon R_b}{\varepsilon r R_b + t_1 t_2}. \tag{3}$$

This equation enables the estimation of the value of A^* for given values of t_j, r, and R_b. One can expect the influence of the surface to be less important for optically thick clouds [$t_j \to 0$, $r \to 1$, $A^* \to 1$; see Eq. (3)]. In this case the value of R_b for nonabsorbing media can be written approximately as[2]

$$R_b = R_\infty - tK_0(\xi)K_0(\eta), \tag{4}$$

where

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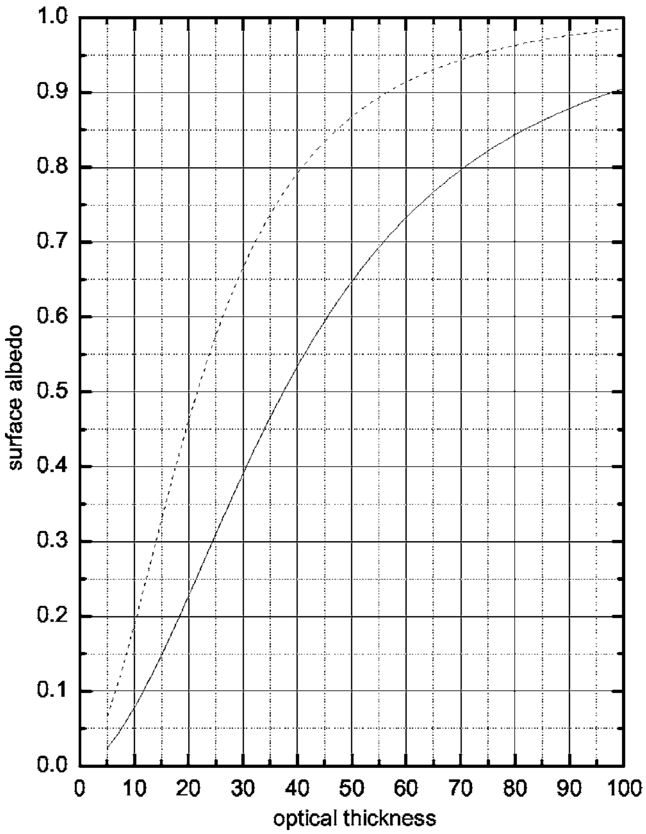

Fig. 1 Dependence of A^* given by Eq. (3) on cloud optical thickness τ for ice (broken line) and water (solid line) clouds for nadir observation and a solar zenith angle of 60 deg.

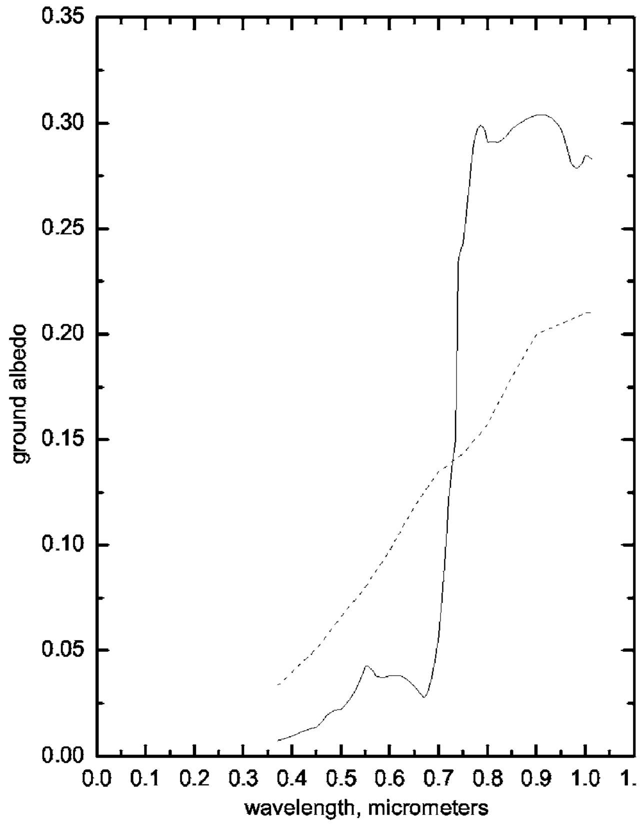

Fig. 2 Spectral albedo of vegetation (solid line) and bare soil (dashed line) (W. von Hoyningen-Huene, private communication).

$$t = \frac{1}{1.072 + 0.75\tau(1-g)}, \tag{5}$$

τ is the cloud optical thickness, g is the asymmetry parameter, ξ is the cosine of the solar zenith angle, η is the cosine of the observation zenith angle, R_∞ is the reflection function of a semi-infinite cloud, and $K_0(\xi)$ is the escape function, which can be written as[2]

$$K_0(\xi) = \frac{3}{7}(1 + 2\xi) \tag{6}$$

for $\xi \geqslant 0.2$. The accuracy of Eq. (4) is studied by Kokhanovsky and Rozanov,[5] who show that Eq. (4) is applicable for $\tau \geqslant 5$. It is easy to demonstrate that[2] $r = 1 - t$, $t_1 = tK_0(\xi)$, and $t_2 = tK_0(\eta)$ for nonabsorbing optically thick turbid media.

The results of calculations of the maximal albedo of the underlying surface [according to Eq. (3)] for nadir observation and a solar zenith angle of 60 deg for optically thick nonabsorbing clouds are shown in Fig. 1 for water clouds (solid line, $g = 0.85$) and for ice clouds (dashed line, $g = 0.75$) at $\varepsilon = 0.05$. The value of R_b was taken from exact radiative transfer calculations for water ($R_b = 0.87$) and ice ($R_b = 0.92$) clouds. It follows that remote sensing of clouds with $\tau \geqslant 5$ over water ($A \leqslant 0.05$) can be performed neglecting the contribution of the surface reflection. Clearly, this is not the case for bright surfaces. For instance, the surface reflectance of snow is typically 0.8 in the visible. For water clouds with the optical thickness 70 and below, the contribution of the snow surface must be taken into account. The correspondent optical thickness is equal to 40 for ice clouds over snow, due to the smaller transmittance of ice clouds than that of water clouds having the same optical thickness.

Land surface reflectance (outside of complex urban areas) can be influenced by a mixture of the spectra of vegetation and bare soil. Some examples are given in Fig. 2. It follows from Fig. 2 that the reflectance can reach 0.3 in the near IR for the vegetation. This means that cloud retrievals over land cannot ignore the contribution from the second term in Eq. (1) (see also Fig. 1), especially for thin clouds. The results of calculations of the spectral cloud reflectance over land using Eq. (4) are shown in Figs. 3 and 4. The step around 0.7 μm is clearly seen in Fig. 3 at $\tau \leqslant 10$. This means that the effect of the surface reflectance is important in this case. The surface effects can be neglected at $\tau > 30$, which is in agreement with Fig. 1. The results for bare soil are shown in Fig. 4. Here we see a slight increase of the cloud reflectance with the wavelength, due to the influence of the underlying surface, at $\tau \leqslant 20$. The slope of the curves decreases with increasing cloud optical thickness.

The reflection function results for water and ice clouds are shown in Fig. 5 at $\tau = 5$. The step in the spectral reflectance curve $R(\lambda)$ is more pronounced for water clouds because water clouds are more transparent (larger values of g)

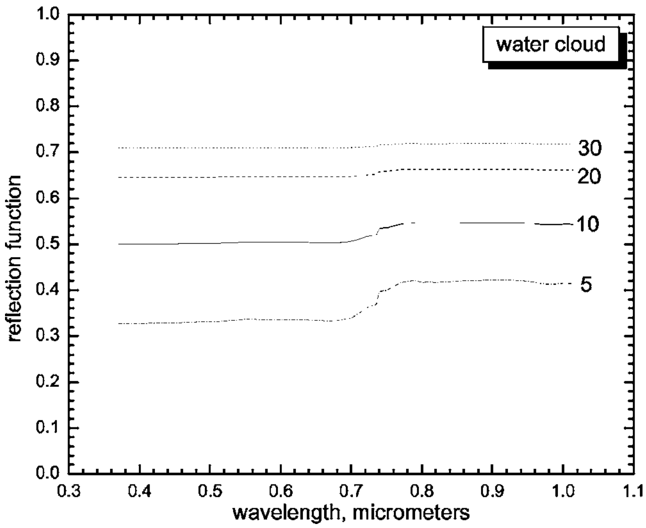

Fig. 3 Reflection function of a water cloud for nadir observation and a solar zenith angle equal to 60 deg, at cloud thicknesses equal to 5, 10, 20, and 30. The spectral albedo of vegetation as shown in Fig. 2 was used in the calculations.

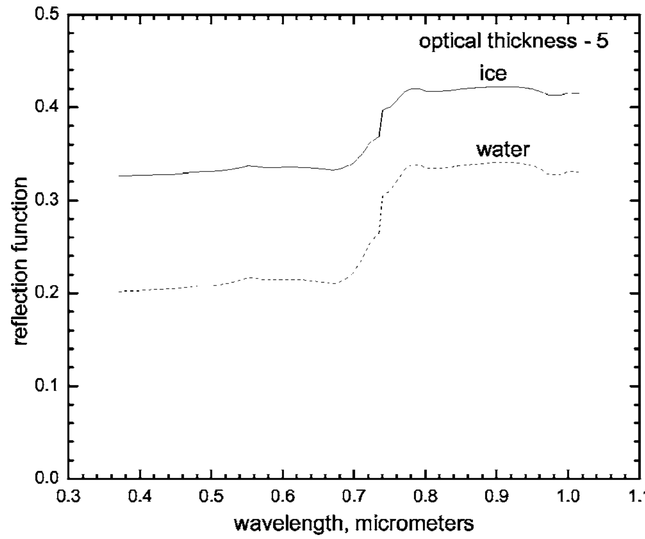

Fig. 5 Reflection function of water and ice clouds over vegetation for nadir observation and a solar zenith angle equal to 60 deg, at cloud thickness 5. The spectral albedo of vegetation as shown in Fig. 2 was used in the calculations.

to light coming from the ground. So the contribution of the surface for water clouds is larger than for ice clouds in the visible.

3 Transmittance

A similar procedure can be followed to study the influence of the ground reflectance on the transmission function T of a cloud. This function is given as[3]

$$T = T_b + \frac{A t_1 r_p}{1 - Ar}, \tag{7}$$

where $T_b \equiv T(A=0)$, r_p is the cloud plane albedo, and the other parameters are the same as in Eq. (1). The value of A^* for the transmitted light can be obtained from Eq. (3) by

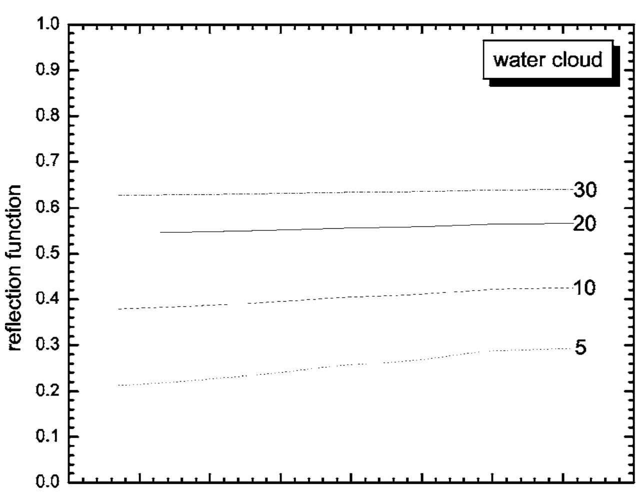

Fig. 4 The same as in Fig. 3, but over bare soil.

replacing R_b with T_b and also replacing t_2 with r_p. It follows that

$$A^* = \frac{\varepsilon T_b}{\varepsilon r T_b + t_1 r_p}. \tag{8}$$

Then using the results of the asymptotic theory for optically thick nonabsorbing clouds,[2]

$$T = tK_0(\xi)K_0(\eta), \quad t_1 = tK_0(\xi), \quad r_p = 1 - tK_0(\eta), \tag{9}$$

we can easily derive the following expression for the threshold value of A^*:

$$A^* = \frac{\varepsilon}{\varepsilon(1-t) - t + K_0^{-1}(\eta)}. \tag{10}$$

This gives a maximal ground albedo of the surface, which must be used in the calculations of T, with accuracy given by the threshold value ε. The dependence of A^* on τ is given in Fig. 6 for ice and water clouds. It is seen that A^* is smaller for ice clouds. This is easily understood. Indeed, ice clouds have smaller values of the asymmetry parameter, and therefore ice clouds having the same optical thickness reflect more and have a much stronger interaction with the ground surface for nonabsorbing channels than do water clouds (in the visible, where light absorption processes can be neglected). So the ground surface plays a larger role in this interaction process. This makes A^* smaller than for water clouds (see Fig. 6).

The dependence of the transmission function on the wavelength for underlying vegetation and for bare soil is shown in Figs. 7 and 8, respectively. The surface reflectance spectra are assumed to be the same as shown in Fig. 2.

It follows that there is some influence of the underlying surface albedo on the transmitted light even for very thick clouds (see Fig. 7). In particular, we see that the transmis-

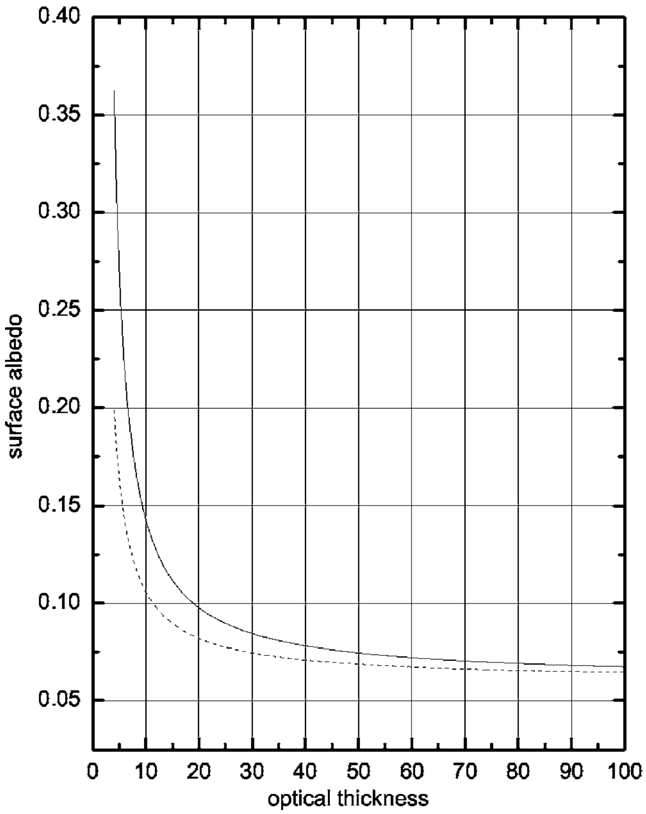

Fig. 6 Dependence of A^* [see Eq. (8)] on cloud optical thickness for ice (broken line) and water (solid line) clouds at the zenith observation (ξ=1).

sion for larger wavelengths is somewhat larger due to the surface reflectance effects. This will lead to a difference between the spectral compositions of the solar light below and above the cloud.

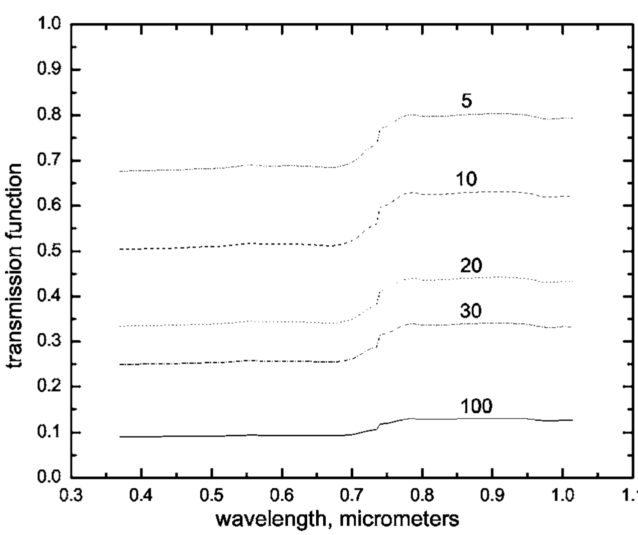

Fig. 7 Transmission function of water cloud for zenith observation (ξ=1) and a solar zenith angle equal to 60 deg at cloud thicknesses equal to 5, 10, 20, 30, and 100. The spectral albedo of vegetation as shown in Fig. 2 was used in calculations.

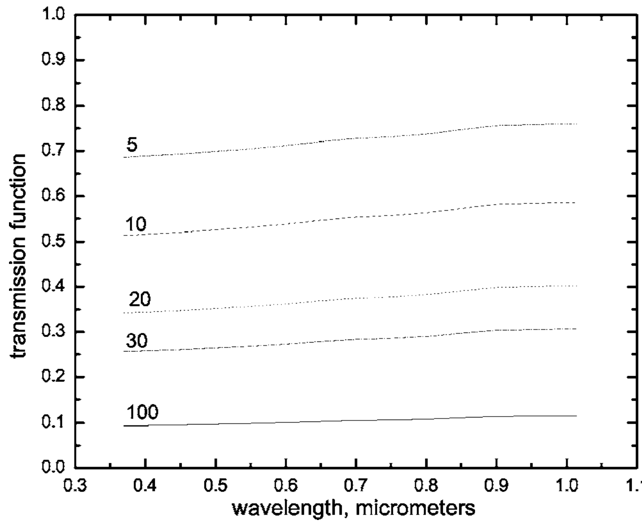

Fig. 8 The same as in Fig. 7, but over bare soil.

4 Conclusions

We have found that the reflection function of water clouds with optical thicknesses larger than approximately 30 can be calculated assuming a black underlying surface. This peculiarity can be used for the simplification of cloud retrieval algorithms over land in the visible and near IR. In particular, it is of advantage to use smaller wavelengths (e.g., in the UV) for cloud remote sensing. Then the influence of the surface is minimized.[6]

For smaller values of τ, one must take account of the surface reflectance both in forward and in inverse modeling. The situation is much alleviated over water, whose light reflectance is generally below 5%. Then the reflectance of light from clouds with $\tau \geqslant 5$ can be treated without consideration of the surface reflectance. This simplifies retrieval algorithms considerably for extended cloud fields. Clearly, the surface contribution cannot be neglected for broken-cloud conditions even if the surface albedo is equal to zero and the optical instrument observes a ground scene with some portions not completely covered by a cloud. Then measurements of $R(\lambda)$ are governed by the cloud fraction. This complex situation, however, is outside the scope of this paper, which deals with the idealized case of horizontally and vertically homogeneous clouds.

Also, the case of diffuse transmitted light has been considered. It was found that the ground surface influences the transmission spectra even for relatively thick clouds. This is in contrast with the reflectance spectrum of an extended cloud field.

Our results suggest that the spectral top-of-atmosphere reflectance measured by a spectrometer on a satellite orbiting a planet can be used to identify the type of the underlying surface underneath (e.g., the presence of vegetation; see Fig. 3) even for the case of a cloudy atmosphere (so long as the ground albedo is larger than the threshold value A^* introduced in Sec. 1).

To conclude, we underline that the theoretical results obtained are of importance for several other applications of optical engineering, including the paint, paper, and textile industries.

Acknowledgments

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A. A. Kokhanovsky graduated from the Physics Department of the Belarussian State University, Minsk, Belarus, in 1983. He has received his PhD degree in optical sciences from the B. I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus, in 1991. The PhD work was aimed at modeling light scattering properties of aerosol media, clouds, and foams. Dr. Kokhanovsky is currently a member of the SCIAMACHY/ENVISAT algorithm development team (Institute of Environmental Physics, University of Bremen). His research interests are directed towards modeling light propagation and scattering in the terrestrial atmosphere and ocean. Dr. Kokhanovsky is the author of the books *Light Scattering Media Optics: Problems and Solutions* (Springer-Praxis, Chichester, 1999, 2001, 2004), *Polarization Optics of Random Media* (Springer-Praxis, Berlin, 2003), and *Cloud Optics* (Elsevier, Amsterdam, 2006). He has published more than 100 papers in the field of environmental optics, radiative transfer, and light scattering. Dr. Kokhanovsky is a member of the editorial board of the *Journal of Quantitative Spectroscopy and Radiative Transfer*, and also serves on the advisory board of the Springer-Praxis Publishing Company. He is an editor of *Light Scattering Reviews* (www.springer.de). Dr. Kokhanovsky is a member of the American Geophysical Union, the European Geophysical Union, and the Belarussian Physical Society.